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MILLISECOND OSCILLATIONS AND PHOTOSPHERIC RADIUS EXPANSION IN THERMONUCLEAR X-RAY BURSTS

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ABSTRACT

We use archival data from the *Rossi X-Ray Timing Explorer* to examine 125 type I X-ray bursts from the 9 weakly magnetic accreting neutron stars where millisecond oscillations have been detected during some bursts. We find that oscillations from the 6 "fast" ($\simeq$ 600 Hz) sources are almost always observed during radius expansion bursts, whereas oscillations from the 3 "slow" ($\simeq$ 300 Hz) sources are about equally likely to be found in bursts both with and without photospheric radius expansion. This strongly suggests that the distinction between these two source groups cannot be an observational selection effect, but must instead arise from some physical mechanism.

Subject headings: stars: neutron — X-rays: bursts — X-rays: stars

1. INTRODUCTION

Nearly coherent 270–620 Hz oscillations have been observed during type I X-ray bursts(Lewin, van Paradijs & Taam 1993) from neutron stars in nine low mass X-ray binaries (LMXBs; see van der Klis 2000 for a recent review). Oscillations may occur because a hot spot forms on the rotating neutron star surface during the burst (Strohmayer et al. 1996). Their frequency evolution has been interpreted in terms of a burning layer that expands by ≈50 m and slows at the start of the burst, only to spin up again over several seconds as the layer contracts (Strohmayer et al. 1997; Cumming & Bildsten 2000).

The pairs of kilohertz quasi-periodic oscillations (kHz QPOs; see van der Klis 2000 for a review) observed in the persistent emission of most burst oscillation sources naturally divide the sources into two categories. The frequencies of these twin kHz QPOs vary by up to a factor of 2, while their separation $\Delta\nu_{\rm kHz}$ varies by at most $\sim$ 40% and suggests the relation $\nu_{\rm burst} \approx n\,\Delta\nu_{\rm kHz}$, with $n = 1$ for the three sources with a "slow" $\nu_{\rm burst} \simeq 300$ Hz and $n = 2$ for the six sources with a "fast" $\nu_{\rm burst} \simeq 600$ Hz (Strohmayer et al. 1996; van der Klis 2000). This relationship between $\Delta\nu_{\rm kHz}$ and $\nu_{\rm burst}$ has been interpreted in terms of a beat frequency model for the kHz QPOs relating the inner accretion disk motion with the neutron star spin frequency, $\nu_{\rm spin}$ (Strohmayer et al. 1996; Miller, Lamb, & Psaltis 1998). This model presumes that $\Delta\nu_{\rm kHz} \approx \nu_{\rm spin}$ and suggests that sources with slow burst oscillations ($n = 1$) have a single visible hot spot on their surface and that sources with fast burst oscillations ($n = 2$) have a pair of hot spots (Strohmayer et al. 1998). This further suggests that all nine sources have $\nu_{\rm spin} \simeq 300$ Hz, and several authors have proposed mechanisms for a natural spin equilibrium near this frequency (White & Zhang 1997; Bildsten 1998). An alternative explanation for the kHz QPOs in terms of relativistic accretion-disk precession has also been proposed (Stella & Vietri 1998; Psaltis & Norman 2000), but it does not explicitly address the relation between $\Delta\nu_{\rm kHz}$ and $\nu_{\rm burst}$.

Millisecond oscillations do not occur in every burst from these nine LMXBs. Muno et al. (2000) found that oscillations from KS 1731−260 are usually observed only in bursts which exhibit photospheric radius expansion, during which the apparent radius of the emission region increases by $\gtrsim$ 20 km because the flux at the surface of the neutron star exceeds the Eddington limit. On the other hand, Franco (2001) and van Straaten et al. (2001) found that bursts from 4U 1728−34 *without* radius expansion exhibited oscillations more often than radius expansion bursts. One common property of both sources is that millisecond oscillations are only observed from bursts which occur on the so-called "banana" branch of their X-ray color-color diagrams, which corresponds to relatively high accretion rates (see van der Klis 1995 for a review of LMXB phenomenology). In this *Letter*, we explore these dependencies of the burst oscillation phenomenon on burst properties by making a comparison between X-ray bursts with and without coherent oscillations in all 9 sources using archival data from the *Rossi X-ray Timing Explorer* (*RXTE*).

2. OBSERVATIONS AND DATA ANALYSIS

We have examined all observations of 8[1] of the 9 burst oscillation sources in the *RXTE* public archive as of 2001 March 22. We searched all of the data taken with the *RXTE* Proportional Counter Array (PCA) for type I bursts and found a total of 125 bursts with data that allowed both timing and spectral analyses. These bursts are summarized by source in Table 1. For the five sources for which detailed burst studies have been published, our results are consistent with the published work (4U 1608−52: Chakrabarty et al. 2001; 4U 1658−298: Wijnands, Strohmayer, & Franco 2001; Aql X-1: Fox et al. 2001; KS 1731−260: Muno et al. 2000; 4U 1728−34: Franco 2001, van Straaten et al. 2001; and 4U 1916−05: Galloway et al. 2001).

[1] Since the localization of bursts associated with MXB 1743−29 is uncertain due to its proximity to the bursting pulsar GRO J1744−28, we use the results from Strohmayer et al. (1997a). For the same reason, the persistent emission cannot be isolated for this source.

In order to characterize the persistent emission, we calculated average soft (3.7–5.1 keV/2.3–3.7 keV) and hard (8.7–18 keV/5.1–8.7 keV) X-ray colors for 256 s intervals using background-subtracted light curves. Location on an X-ray color-color diagram is a good tracer of the accretion rate $\dot{M}$ (see van der Klis 1995 and references therein). KS 1731−260 (Muno et al. 2000) and 4U 1728−34 (Franco 2001; van Straaten et al. 2001) exhibit bursts over the widest range of $\dot{M}$, while cursory checks of the color-color diagrams for the other sources suggest that bursts were only observed at high accretion rates because few or no observations were made during low $\dot{M}$ intervals.

To search for oscillations, we created twice-oversampled power spectra for 2 s intervals of data every 0.25 s for the duration of each burst. If oscillations are detected within ±3 Hz of the expected frequency and within 10 seconds after the start of a burst with a probability $< 2 \times 10^{-4}$ that the signal is due to Poisson noise in a single trial, we consider the oscillation to be a detection. We also used this technique to search all of the bursts for oscillations at the first three harmonics of the slow oscillations, and at 0.5, 1.5, and 2.0 times the frequency of the fast oscillations. We found no evidence for oscillations at these frequencies in any of the bursts. Using power spectra of 1 s intervals, we can place upper limits on the fractional RMS amplitude of oscillations at these frequencies of 5–15% during a burst. These are not very stringent upper limits, so application of more sensitive search techniques such as those described in Miller (1999), Muno et al. (2000), and Strohmayer (2001) will be useful for more detailed studies.

We produced energy spectra for each 0.25 s interval from each burst using available combinations of data modes which provide at least 32 energy channels. We subtracted spectra from 15 s of emission from before the burst to account for background, and fit each spectrum between 2.5–20 keV with a model consisting of a blackbody multiplied by a constant interstellar absorption (determined from the mean value from fits using variable absorption). The model provides an apparent temperature ($T_{\rm app}$) and a normalization equal to the square of the apparent radius ($R_{\rm app}$) of the burst emission surface, and allows us to estimate the bolometric flux as a function of time. The peak flux of bursts from a given source can vary by a factor of 5–10. In many bursts, photospheric radius expansion is evident at the start of the burst, during which $R_{\rm app}$ increases and $T_{\rm app}$ decreases such that the bolometric flux remains constant, presumably at the Eddington limit (see Lewin et al. 1995). Our definition of radius expansion includes bursts which exhibit a second increase in radius immediately after the minimum which follows the expansion phase. We find several such bursts from 4U 1728−34 (see also van Straaten et al. 2001), and one such burst from both 4U 1916−053 and 4U 1608−52.

3. RESULTS

A summary of our results for the nine burst oscillation sources is given in Table 1. There is a tight connection between the presence of oscillations and of radius expansion in fast (≃ 600 Hz) sources from every perspective. Fast oscillations occur predominantly during bursts with radius expansion, and almost all bursts with radius expansion exhibit oscillations. At the same time most of the bursts without fast oscillations also lack radius expansion. In slow (≃ 300 Hz) sources, there is no preference for whether bursts with or without radius expansion exhibit oscillations. This suggests that the frequencies of burst oscillations and the properties of bursts are connected.

Although the sample of bursts from an individual source is in some cases quite small, the correlations for fast and slow sources as groups are quite significant. In order to quantify the significance of our results, we hypothesize that radius expansion occurs in bursts with a fixed probability, f. Given a sample of m bursts, the probability of observing a number n of bursts with radius expansion is

$$P(n|f,m) = f^n (1-f)^{m-n} \frac{m!}{n!(m-n)!}.$$

We can then compute the probability density for f given n radius expansion bursts in a sample of m bursts, $p(f|n,m)$. We have plotted these probability densities in Figure 1 for fast and slow sources, considering as our sample population either all observed bursts (dashed line) and only those bursts which exhibit oscillations (solid line). Although fast and slow sources exhibit radius expansion in about equal fractions of bursts in general, fast sources exhibit radius expansion during bursts with oscillations far more often (88^{+4}_{-8}% of the time) than slow sources (31^{+10}_{-6}%). The trends for individual sources are interesting in that they follow the behavior expected from considering the sources as groups (Figure 2). On the other hand, slow sources are more likely to show radius expansion during bursts *without* oscillations (53^{+9}_{-8}%) than fast sources (20^{+10}_{-5}%).

We can rule out some observational selection effects as causes for these correlations. For example, we are not systematically missing oscillations from weak bursts, as might occur if all oscillations had the same fractional amplitude. We observe oscillations in some of the weakest bursts from KS 1731−260, 4U 1636−53, 4U 1916−053, and 4U 1728−34, while no oscillations are detected during some of the stronger bursts from these sources. Therefore, our correlations are based upon genuine variations in the strengths of the oscillations.

However, since bursts were observed from only two sources at low $\dot{M}$ (KS 1731−260 and 4U 1728−34), there is a remote chance that these correlations are an artifact of the higher $\dot{M}$ at which the remaining sources were observed. For instance, the bursts with the longest time scales take place at low fluxes in 4U 1608−52 (Murakami et al. 1980) and at low inferred $\dot{M}$ in 4U 1636−536 (van der Klis et al. 1990). It is reasonable to believe that these long bursts do not exhibit radius expansion (as in KS 1731−260; see for example Muno et al. 2000), so there would be no strict relationship between radius expansion and fast oscillations if these bursts exhibit oscillations. However, we would consider this a surprise given the absence of oscillations at low accretion rates in KS 1731−260 and 4U 1728−34. On the other hand, the time scales of bursts from the slow oscillators 4U 1916−053 (Swank, Taam, & White 1984) and 4U 1702−429 (Makishima et al. 1982) have not been observed to vary systematically with the persistent flux, so we cannot predict how observing bursts at low $\dot{M}$ in slow sources would affect our correlations.

4. DISCUSSION

We have found that oscillations from the 6 fast burst oscillation sources are tightly connected to photospheric radius expansion, whereas oscillations from the 3 slow sources are about equally likely to be found in bursts both with and without radius expansion. What drives this correlation remains to be determined: is it the burst properties themselves, the oscillation frequencies, or some unseen third parameter?

According to the beat frequency model of kHz QPOs, the fact that $\nu_{\rm burst} \simeq \Delta\nu_{\rm kHz}$ for the "slow" sources whereas $\nu_{\rm burst} \simeq 2\Delta\nu_{\rm kHz}$ for the "fast" ones can be accounted for if one or two antipodal hot spots on the surface of the rotating neutron star are visible to the observer (Miller et al. 1998). One possibility is that the distinction between fast and slow oscillations is due to a difference in the orientation of the hot spots and the observer with respect to the rotation axis of the star. This seems unlikely. Radius expansion is observed with similar likelihood from both fast and slow sources, and therefore is unlikely to depend on our viewing angle. We would not expect oscillations to be associated with radius expansion bursts only in the fast sources if viewing angle effects determine whether one or two spots are observed.

It also does not appear that the strengths of the bursts determine the oscillation frequencies by igniting either one or two hot spots. If this were the case, one would expect to detect slow oscillations during weak bursts without radius expansion from the fast sources, and fast oscillations during strong bursts from the slow sources. Out of the 125 bursts we observed from sources of burst oscillations, we find no evidence for harmonic or half-frequency signals with powers comparable to the signals at the frequencies in Table 1.

If the distinction between slow and fast oscillators is equivalent to a division between slow and fast rotators, $\nu_{\rm spin}$ (or some related quantity, e.g., the effective surface gravity) could determine which bursts show oscillations. However, that option is not free of complications, as the transition between the burst properties for sources that exhibit fast and slow oscillations must be very sharp, since the two populations are not at all well separated in frequency (see Table 1). When comparing the observed distribution of $\nu_{\rm burst}$ to a uniform distribution of frequencies between 250–650 Hz, a Kolmogorov-Smirnov test (e.g., Eadie et al. 1971) can exclude a uniform distribution at only the 1.3σ (81%) confidence level. It is interesting to note that the recent report of a possible ≈ 400 Hz burst oscillation from the 401 Hz pulsar SAX J1808.4−3658 (in 't Zand et al. 2001) would make the $\nu_{\rm burst}$ distribution even more consistent with a uniform distribution (excluded at only the 0.9σ or 64% confidence level), so the putative transition would have to be correspondingly sharper.

We have listed a few additional properties of these LMXBs in Table 1. Neither the activity level nor the long-term average accretion rate $<\dot{M}>$, as determined from nearly 5 years of data from the *RXTE* All-Sky Monitor (Levine et al. 1996), appears to be correlated with the frequencies of the burst oscillations. Fast oscillations are observed in both transient (4U 1608−52 and Aql X-1) and persistent (e.g., 4U 1636−53) sources, as well as from both low $<\dot{M}>$ and high $<\dot{M}>$ sources. Orbital periods are measured for only 4 of the 9 sources, and range from 0.81 to 19 hours. It is apparent that these burst oscillation sources are an inhomogeneous group, which makes measurements of oscillations from other sources highly desirable.

We feel that the most likely explanation for the observed correlations is that the burst properties change differently as a function of $\dot{M}$ in fast and slow sources. X-ray burst theory predicts that radius expansion should occur only at low $\dot{M}$ (Fujimoto, Hanawa, & Miyaji 1981; Ayasli & Joss 1982). This agrees with observations of the slow oscillator 4U 1728−34 (Franco 2000; van Straaten et al. 2000), but does not appear to hold true for the fast oscillators KS 1731−260 (Muno et al. 2000), 4U 1608−52 (Murakami et al. 1980), and 4U 1636−53 (van der Klis et al. 1990). If oscillations only appear at high $\dot{M}$ (as suggested by Franco 2001), then they would indeed be associated with radius expansion in the fast sources, but not the slow sources. Furthermore, Bildsten (2000) has suggested that some mechanism acts in these latter sources to confine the accreted material such that the *local* $\dot{M}$ can decrease even as the global $\dot{M}$ increases. If this is true, such confinement is somehow related to the higher frequency of the fast burst oscillations.

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Table 1
Burst Oscillations (BOs) and Photospheric Radius Expansion (PRE)

Source Name	$\nu_{\rm burst}$ (Hz)	Total Bursts	Number (Percentage) of Bursts: BOs PRE	no BOs PRE	BOs no PRE	no BOs no PRE	$F_{\rm ASM}$[a] (c s^{-1})	D (kpc)	$P_{\rm orb}$ (hr)	Ref.
Fast Oscillators										
4U 1608−52	620	6	2 (33%)	0	0	4 (67%)	3.36	4.0	···	[1,2]
MXB 1743−29	589	3	3 (100%)	0	0	0	···	···	···	[3]
4U 1636−53	581	16	12(75%)	0	2 (13%)	2 (13%)	14.55	6.5	3.8	[2,4,5]
4U 1658−298	567	15	5 (33%)	5 (33%)	1 (7%)	4 (27%)	0.74	10[b]	7.1	[4,6]
Aql X-1	550	10	3 (33%)	1 (10%)	0	6 (60%)	2.79	4.8	19	[2,7,8]
KS 1731−260	521	13	4 (31%)	0	1 (4%)	8 (62%)	10.12	7	···	[5]
Total Fast		60	26 (46^{+7}_{-6}%)	6 (10^{+5}_{-3}%)	4 (6^{+5}_{-1}%)	24 (38^{+7}_{-5}%)[c]				
Slow Oscillators										
4U 1728−34	363	49	11 (22%)	11 (22%)	16 (33%)	11 (22%)	6.58	4.3	···	[10,11,12]
4U 1702−429	330	8	0	0	7 (87%)	1 (13%)	3.50	6.7	···	[4,12]
4U 1916−053	270	8	0	5 (50%)	1 (10%)	2 (20%)	1.21	10	0.83	[2,13,14]
Total Slow		65	11 (17^{+6}_{-3}%)	16 (25^{+6}_{-4}%)	24 (37^{+7}_{-5}%)	14 (22^{+6}_{-4}%)[c]				

[a] Mean 1.5-12 keV count rate observed with *RXTE*/ASM.

[b] Distance was derived assuming the peak flux from the brightest burst observed with *RXTE* represents the Eddington luminosity for pure helium.

[c] 1-σ uncertainties derived assuming a binomial distribution (see text).

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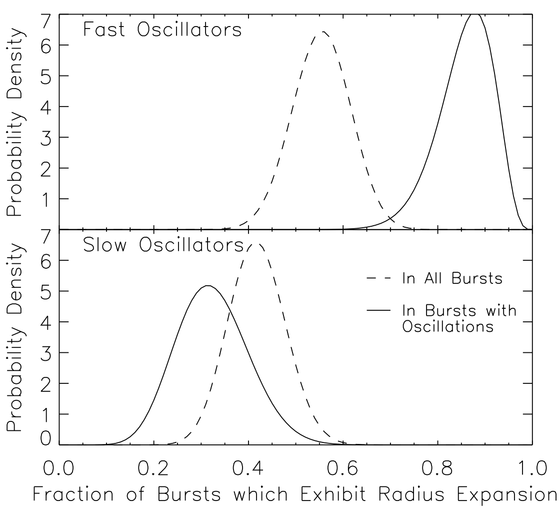

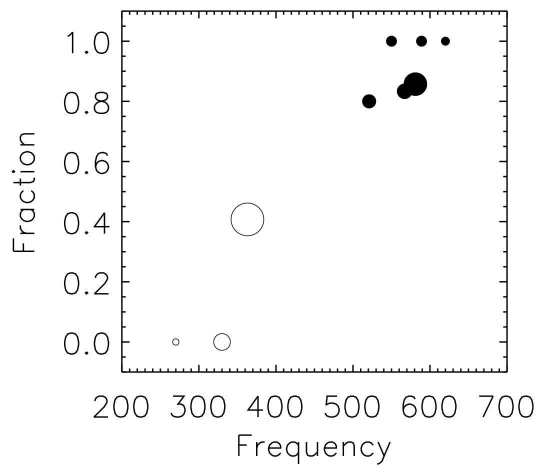

FIG. 1.— The probability that radius expansion bursts occur in a given fraction of all bursts (*dashed line*) and of bursts in which oscillations are observed (*solid line*), assuming that the number of radius expansion bursts out of a sample population is distributed according to a binomial distribution.

FIG. 2.— The fraction of bursts with oscillations that are also radius expansion bursts, plotted as a function of source oscillation frequency. Open circles denote slow ($n = 1$) oscillation sources, while solid circles denote fast ($n = 2$) oscillation sources. The size of the circle indicates the number of bursts with oscillations observed for each source.